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Technical Report No. 32-182

Strain Measurements on a Pressurized Solid Propellant Grain

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PASADENA, CALIFORNIA

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Note:
The work reported herein is undertaken in partial fulfillment of the Advanced Research Projects Agency Letter Order No. 107-60, for the National Aeronautics and Space Administration.

ABSTRACT

Measurements of the principal strains existing on the end cross section of five different solid propellant grains were made for two loading conditions, using the photoelastic coating technique. Surface re-enforcing effects were minimized by the application of a low-modulus (500 psi) birefringent resin as the coating medium. The principal stresses in the coating were separated by a graphical procedure. The results indicate that the coating technique gives a more realistic measurement of grain stress concentrations and surface strain magnitudes, and that stress measurements obtained from classical model theory are quite conservative.

I. INTRODUCTION

The contemporary study of solid propellant physical properties is largely guided by stress analyses based on classical infinitesimal elastic theory (Ref. 1, 2, and 3). Experimental techniques used to measure metal physical properties are usually inadequate to measure the physical properties of the rubber-like solid propellant. The physical composition of the propellant grain consists of crystalline oxidizer imbedded in a rubber which consists of long, entangled, and occasionally linked molecular chains. The material may have peculiar physical properties such as contracting with increasing temperature under a tension load, and longitudinally extending under torsion; working strains may be of the order of 10 to 30%.

Theories of nonlinear viscoelasticity, even if simplified (Ref. 4, 5, and 6) cannot be exploited satisfactorily until methods of measuring strains in and on the grains are improved. The lack of knowledge of the experimental principal strain magnitudes, directions, and locations has retarded the progress of the theorist. Usually, simplified strain distributions are assumed intuitively and are introduced for the purpose of facilitating the mathematics. However, if realistic strain data can be obtained, the solution of advanced theories, although difficult, would be worthwhile.

One experimental method that has been used to describe stress–strain fields in propellant grains is the classical photoelastic technique (Ref. 7 and 8). This technique consists of studying the stress–strain fields in rigid plastic models. Such models have the undesirable feature of not being viscoelastic and of having physical properties unlike the propellants. Usually, the resulting measurements obtained from plastic models can only indicate stress concentration regions in general terms.

Physical property problems concerning viscoelastic media should be solved using strain data of the actual viscoelastic media. Determination of such strain data in actual viscoelastic media may be accomplished by application of the photoelastic coating technique. The physical property requirements of the coating material are met by a linear, low-modulus elastomer (linear physical and sensitive stress optical properties; elastic modulus <500 psi). The object of this study was to extend the photoelastic coating technique directly to strain measurements on viscoelastic solid propellants, and to illustrate the experimental procedure and the analytical technique required to evaluate linear or nonlinear strains on the surfaces of propellant grains.

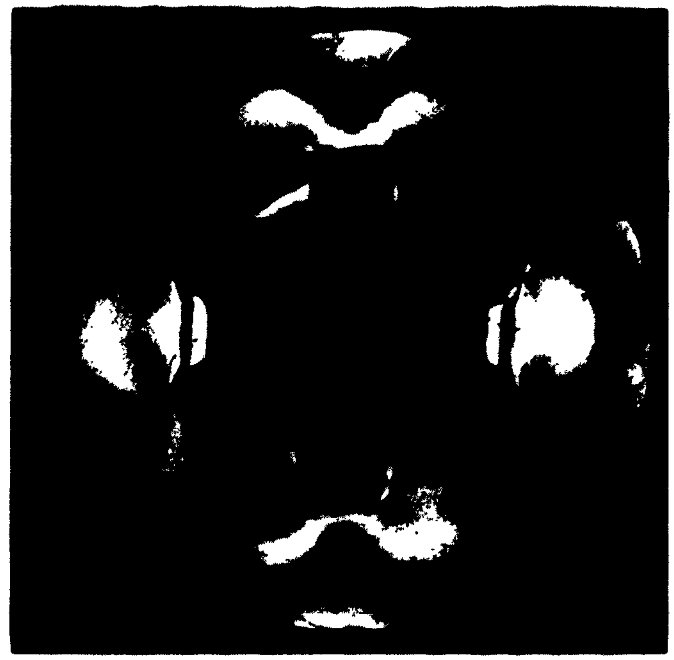

Fig. 1. Radially unrestricted propellant grain, internal pressure of 60 psi

The question of finding a suitable birefringent coating resin was resolved by the fact that many high polymer resins are birefringent (Ref. 9). Using such a resin coating, the strains on the end surface of five solid propellant grains were measured for an internally pressurized two-dimensional grain loading condition (Fig. 1). The specimens were pressurized both as external radially free and external radially fixed.

II. BIREFRINGENT COATING

The birefringent resin material used in this study had the following physical and stress–optical parameters:

(1) Thickness = 0.110 in.

(2) Elastic modulus = 530 psi.

(3) Poisson's ratio = 0.45, at 15% strains, although for small strains Poisson's ratio = 0.50.

(4) Stress–optical sensitivity = 15.9 psi fringe.

A sheet of the resin was cut to match the end of the grain and the edges trimmed to ensure noncontact with the pressurizing device, or outer cylinder when employed. The resin was coated on one side with aluminum paint before bonding it to the grain.

Parasitic birefringence was not observed. This may have been due to the low stress–optical coefficient of the resin compared to contemporary birefringent materials.

The assumption that the strains in the resins were those experienced by the propellant seemed to be valid upon further inspection of the bonding after loading. Any reinforcing effect of the resin coating is minimized by its low modulus and its inherent material properties that are similar to propellants in general.

III. PRESSURIZING SYSTEM

The propellant grain was pressurized by the use of a contoured inflatable rubber bag, confined by tapered end plates (Fig. 2). The end plates were tapered to follow the port configuration of the grain for either longitudinal contraction or expansion. The distance between the end plates could be varied by a loading fixture, depending on whether the grain expanded or contracted axially under pressure. The end plates served to: (1) maintain an unobstructed view at one end of the grain, (2) retain the rubber bag within the grain, and (3) approximate a plane–stress two-dimensional loading. The end plates were adjusted to contain the bag with a minimum amount of longitudinal stress on the grain. This technique allowed the grain to expand or contract longitudinally without inducing a stress in the longitudinal direction. A plane-stress condition was approximated for the external radially fixed grains by lubricating the surface between grain and metal container.

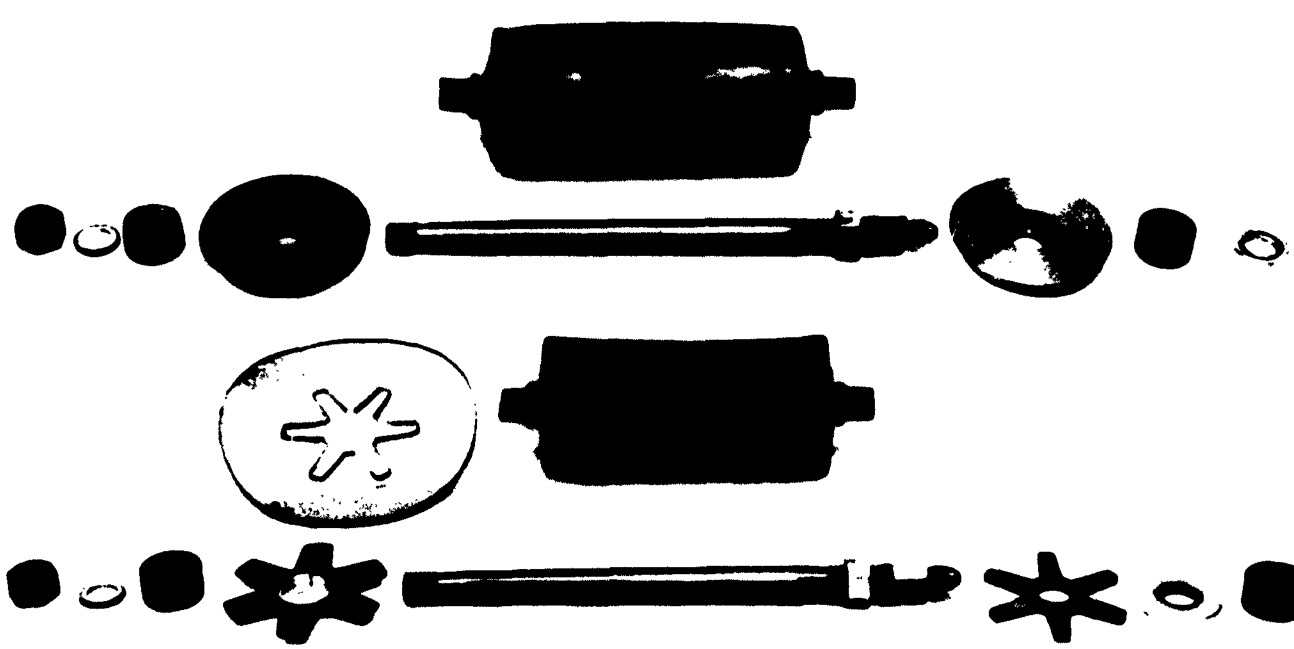

Fig. 2. Typical contoured-bag containment apparatus

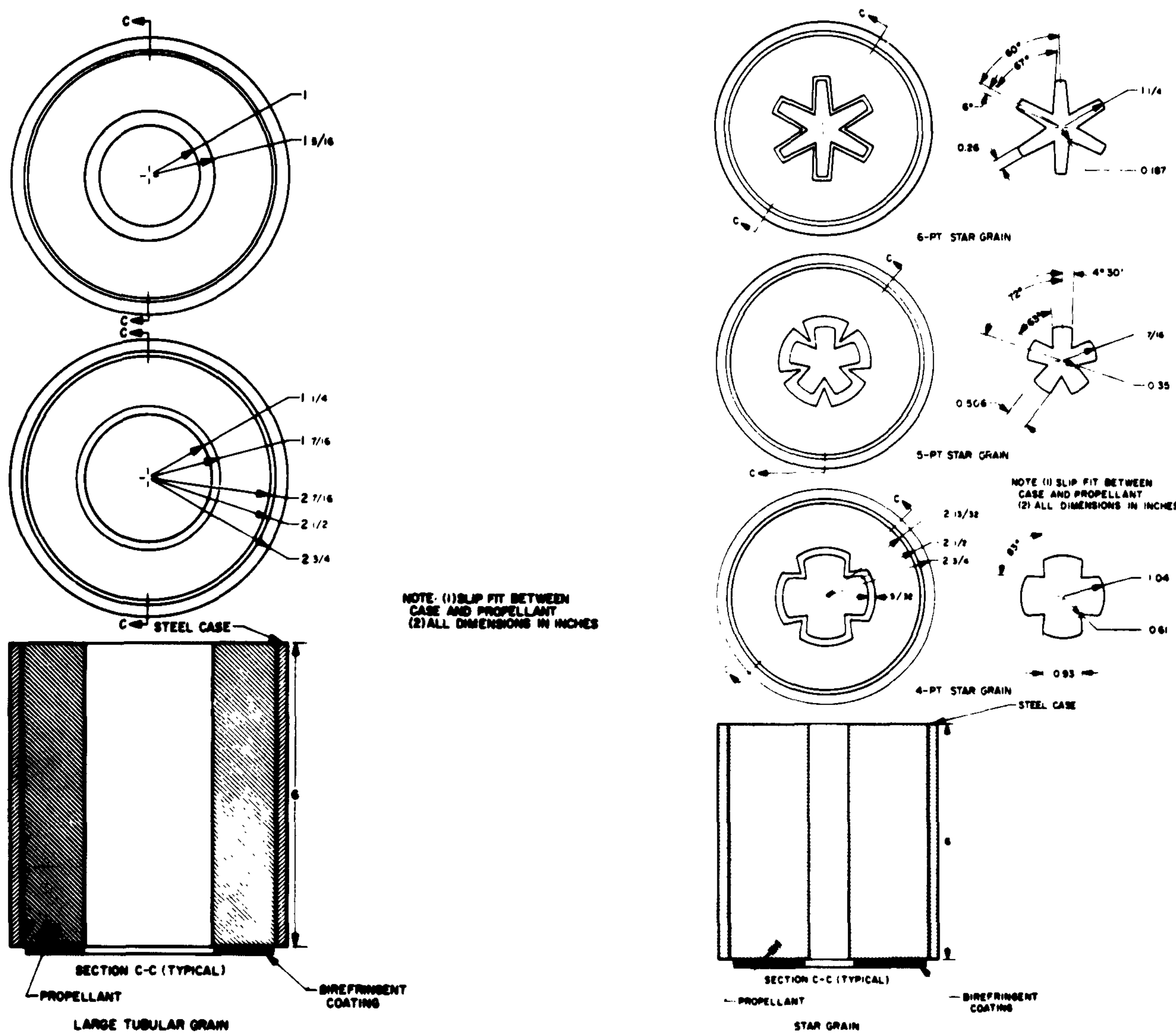

Fig. 3. Five geometries investigated

IV. PROCEDURE

The five geometries chosen for examination are shown in Fig. 3. The individual grains were vertically mounted in a loading fixture. An internal pressure of 60 psi was applied to the free grains and a pressure of 150 psi was applied to the restrained grains. Seven photographs were taken, in all, for each grain. These consisted of one photograph at 0 deg with the quarter-wave plates in view, and six photographs at 0, 15, 30, 45, 60, and 75 deg without the quarter-wave plates in view.

Photographic data were recorded on color positive film (ASA 160) by means of a camera polariscope. The incident polarized white light was approximately normal to the model surface. This was accomplished by using an annular strobe light fitted with crossed polaroid filters. The small diameter light fit over the camera lens and approximated collimated light quite well. Quarter-wave plates were fit to the camera to eliminate most of the isoclinic traces when it was deemed desirable. The reference angular position of the camera was insured by means of a camera mounting graduated in 15-deg intervals. Isoclinic and isochromatic data were graphically recorded from the color film by means of an enlarger.

V. DATA REDUCTION

The graphical method used to separate the principal stresses in the resin coating is a simple and straightforward mechanical manipulation of the data. This method is the basis of the analysis; the photoelastic coating technique has limited values if the magnitudes and directions of principal strains cannot be simply reduced.

Figures 4 and 5 illustrate the typical graphical procedure used to separate the principal stresses in the

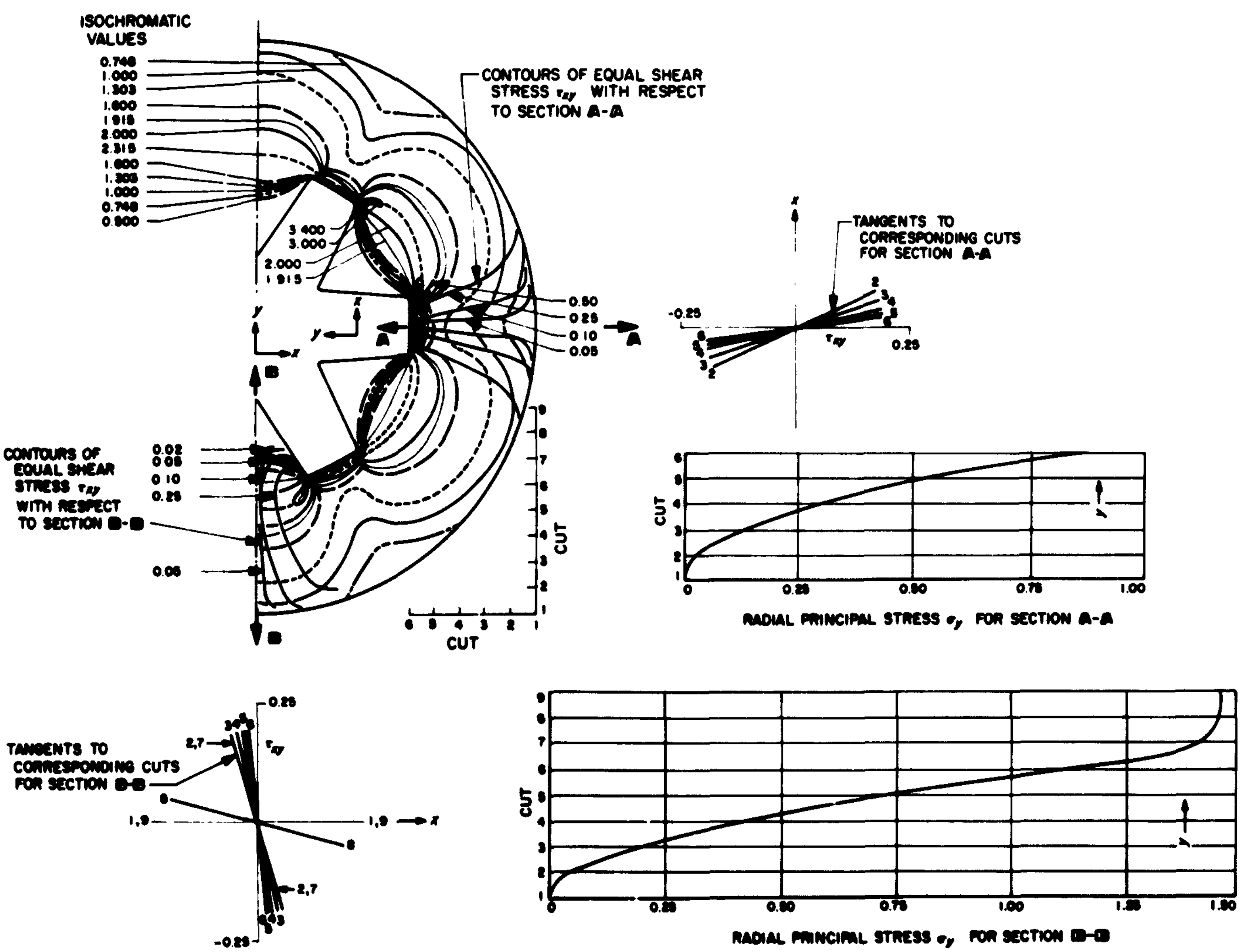

Fig. 4. Typical graphical data reduction to separate principal stresses in coating for free star grain, 60 psi

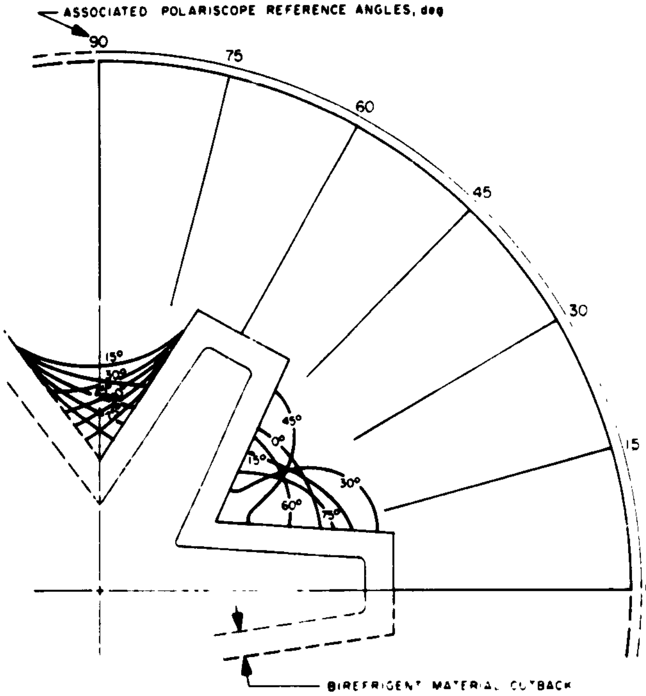

Fig. 5. Typical graphical data reduction to separate principal stresses in coating: isoclinic plot

resin coating. In essence, the procedure is to graphically trace on a vellum the isochromatics and isoclinics from a projected enlargement of the color films. A section to be investigated is chosen and a Cartesian coordinate system (x, y) established. The shear stress trajectories (τ_{xy} = constant) are then superimposed on the vellum. This is readily accomplished by the well known relationships between shear stress (τ_{xy}), normal stress (σ_x, σ_y), and their associated directions (θ). Thus, the shear stress magnitude is known for any point in the vicinity of the section under investigation.

$\partial\tau_{xy}/\partial x$ and $\partial\tau_{xy}/\partial y$ are the slopes of their respective τ_{xy} vs x and τ_{xy} vs y curves. These latter curves are found directly from the shear stress trajectories, since the magnitude of the shear τ_{xy} changes along any cut perpendicular to a given section. $\partial\sigma_y/\partial y$ may be found by graphically noting the geometric relationship (negative reciprocals of slopes) established by the two-dimensional equilibrium equation

$$\frac{\partial\tau_{xy}}{\partial x} + \frac{\partial\sigma_y}{\partial y} = 0 \qquad (1)$$

Knowing $\partial\sigma_y/\partial y$ at various points, σ_y vs y may be determined by curve fitting. σ_x is then analytically determined from the isochromatic readings ($\sigma_x - \sigma_y$). With these stresses known, the corresponding strains in the linear elastic coating are found.

VI. DISCUSSION AND CONCLUSION

The radial and circumferential strain distributions in the radially nonrestricted grain are shown in Fig. 6a and b. Similarly the corresponding strains for the radially restricted grain are shown in Fig. 6c and d.

In Ref. 10, where a more detailed discussion is found, it is shown that contemporary infinitesimal elastic theory regarding elastic tubular gains predicts strains that are quite conservative compared to those measured by the photoelastic coating technique. These discrepancies are due in part to the relatively large strains (10 to 15%) associated with the grains.

Fringe concentrations, normally associated with photographs of propellant grain models found in the literature, were observed by loading the resin laterally with a sharp instrument. This indicates that the resin is relatively sensitive to stress concentrations. However, stress concentrations were never observed for actual propellant grains as high as are reported by the numerous investi-

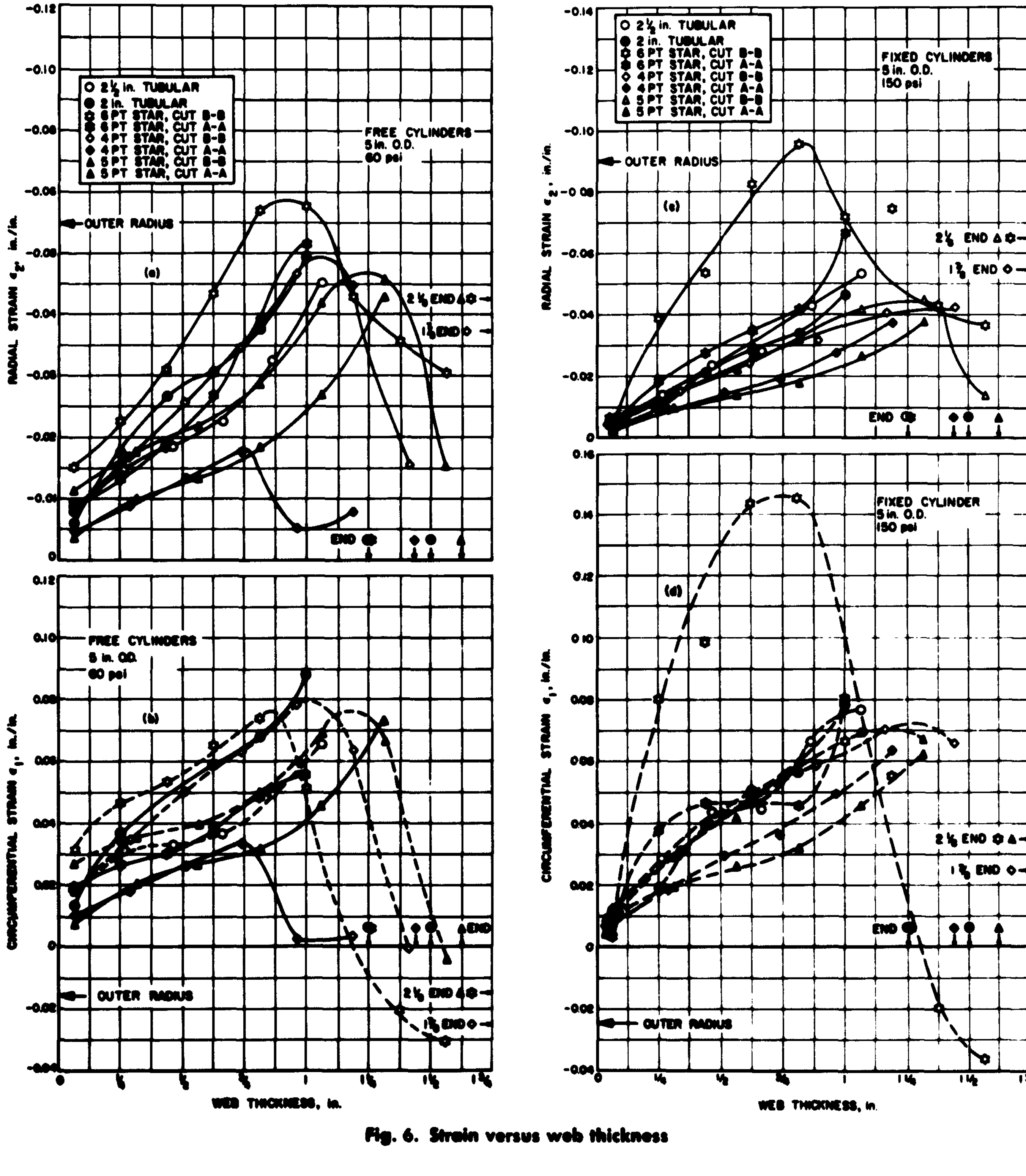

Fig. 6. Strain versus web thickness

gators of plastic models. This is possibly a result of the viscoelastic nature of the propellant but cannot be due to a low stress–optic sensitivity.

As an example, Ordahl and Williams (Ref. 7), using classical photoelastic data, predict an interior stress concentration factor $K_i = 2.6$ which, in turn, predicts a circumferential stress $\sigma_{\theta_i} = 354.0$ psi. These predictions are for the 5-in. diameter, unrestrained six-pointed star pressurized at 60 psi (Fig. 1). The maximum tensile stress of propellants at ambient temperatures is usually less than 200 psi. However, the strain data of a grain of these dimensions and pressure (Fig. 5a and 5b) indicates that the propellant grain was experiencing relatively moderate strains. Results to date clearly show an inadequacy in propellant grain analyses, in that strains and stress concentration factors thus determined are too conservative based on infinitesimal classical elastic theory and photoelastic analysis using models.

The photoelastic coating technique is amenable to the measurement of strains on the surface of propellant grains and other viscoelastic materials. The accumulation of such measured data along with known boundary stresses should eventually supply the information needed to compute realistic propellant physical properties for biaxial loading. This nondestructive method of measuring strains should facilitate further studies with nonlinear viscoelastic materials.

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